

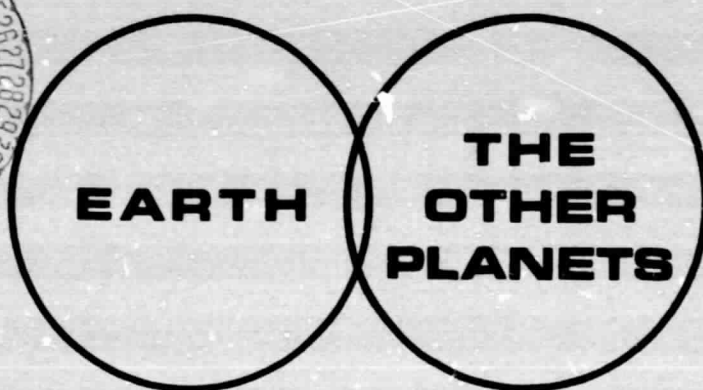
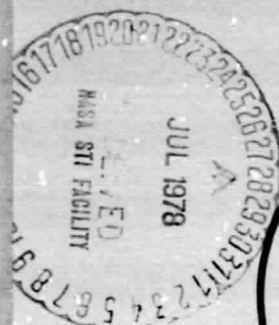
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Dynamics of Earth and Planetary Atmospheres

A Brief Assessment of Our Present Understanding



Report of the
Planetary Atmospheres Workshop
July 10-16, 1977
Snowmass, Colorado

Sponsored by
National Aeronautics and
Space Administration
and
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16. Abstract This report which documents the Planetary Atmospheres Workshop held on July 10-16, 1977, at Snowmass, Colorado, assesses the present understanding of planetary atmospheres, the application of this knowledge to terrestrial problems, and the research needs in these overlapping areas. The workshop was sponsored by two programs within NASA: the Office of Space Science and the Office of Applications. Participants included representative researchers from planetary atmospheric sciences and earth atmospheric sciences in order to consider how the greatest advantage can be reaped from an opportunity to look at planets other than the earth.			
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PREFACE

This Workshop has been sponsored by two programs within NASA, the Office of Space Science and the Office of Applications. There is a message in this. As the cover of this document shows, exploratory and basic research on planetary atmospheres strongly overlaps earth atmospheric studies in both theory and observation. The purpose of this document is to assess our present understanding of planetary atmospheres, the application of this knowledge to terrestrial problems, and the research needs in these overlapping areas.

During the Workshop one impression was dominant, namely that progress in our understanding of planetary atmospheres in general and that of the earth's atmosphere in particular has been greatly advanced over the last couple of decades. For this we can thank developments in theory, the availability of high-speed computers, instrumented satellites, and planetary missions. More questions remain to be resolved, but it is because of our impressive progress that the questions can be so detailed.

The Snowmass Workshop brought together representative researchers from Planetary Atmospheric Sciences and Earth Atmospheric Sciences to see how the greatest advantage can be reaped from an opportunity to look at planets other than our own. We attempted to assess progress in the application of existing observations to planetary atmosphere theory and to identify gaps in both theory and observation.

The number of participants and the short time limited the number of planets we could consider. Lack of mention of other planets or atmosphere-bearing satellites should not be construed as lack of interest in them. Our understanding of Venus, Mars, and Jupiter has reached a relatively advanced level, yet with each of these objects, significant and valuable surprises have emerged. We may surely anticipate other important atmospheric discoveries as we begin to explore Saturn, Titan, and the other planets.

We make no attempt to justify a planetary space program solely in terms of practical benefits that could accrue. Many will indeed accrue, but we are concerned here with basic research. We assumed that the United States will continue to support a civilian program in space in any event, and we set ourselves the task of seeking ways to maximize the benefit to earth-oriented studies that such an opportunity presents.

At the plenary sessions, position papers which addressed both the theories and the observations were presented. Although the central theme was the fluid dynamical aspect of planetary atmospheres, neither the terrestrial climate nor the climates of the other planets can be divorced from other physical or chemical processes. Consequently, implications of results in planetary chemistry, aeronomy, and radiative transfer were also considered. Some of the questions considered at the Workshop included:

- (1) What has been learned from these studies that advances our knowledge of the common properties of planetary atmospheres?
- (2) What new observations can be expected to contribute further to planetary atmosphere and climate theory?

In any large exploratory and research program one can ask:

"What should be done?"

"What can be done?"

"What will be done?"

Answers to the first two questions to a large extent determine what will be done. In the section on observations, we have only asked, "What should be done?" We have tried to provide the answers without regard to a requirement that, at the moment, it indeed can be done. That question must be left to another time--probably to another group.

This group has made no specific recommendations; this would require a more detailed study of measurement possibilities. However, a number of general classes of observations which are needed to meet these goals were identified.

We have also identified several specific terrestrial problem areas in which prior planetary studies have speeded developments. These include parameterizations of radiative heating, the photochemistry of the stratosphere, and parameterizations of heat transport by large-scale eddies for use in climate models. Such examples can be expected to become more numerous in the future as this new field of comparative planetary climatology continues to evolve.

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We wish to acknowledge the support of NASA and the Jet Propulsion Laboratory for this study. The opportunity to consider these issues at Snowmass has been beneficial to us as participants, and we hope that it will be to the larger community as well. The effort could not have succeeded without the dedicated efforts of Ms. Vicki R. Epps of the University of Wisconsin and Ms. Carol L. Snyder of JPL in handling meeting arrangements, typing drafts and final versions of the manuscript, and supervising the final editing.

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SECTION I

INTRODUCTION

It has been recognized for many years that, like the earth, most of the planets of our solar system possess atmospheres. Despite their individual characteristics, these atmospheres possess many features in common with our own. For example, they are not homogeneous gaseous envelopes; nearly all of them have clouds.

A topic involving the earth's atmosphere which has gained international prominence during the past decade is the problem of climate. Our concern is not so much with the determination and explanation of the present climates of various regions of the globe as with the realization that these climates have been changing in the past, and will presumably continue to change in the future. We would like to know what specific changes we can anticipate in the coming decades, as a result of either natural processes or human interference. We must face the very real possibility that some of the coming climatic changes will be detrimental to the continuation of society on our crowded planet.

The other planets possess their own climates. These are likewise subject to changes which may be as catastrophic as the ice ages which the earth has experienced.

We might raise the question as to whether we must study the atmospheres of other planets in order to solve our own climatic problem. Here the answer is clearly "No." For let us suppose that we lived in a solar system with an earth just like our own, but with no other planets. When faced with the problem of explaining climatic changes, would we throw up our hands and say, "We can't do it, we don't have other planets to study?" Presumably we would not; more likely the possibility of other planets would not occur to us at all, and we would attack the problem with the means available.

If instead we raise the question as to whether studying the atmospheres of other planets can aid us in solving our climate problems, the answer is just as surely "Yes." To support such a reply, let us turn first to a page in meteorological history.

One of the most important meteorological works of the eighteenth century was Hadley's explanation of the trade winds--the rather steady winds blowing over the subtropical oceans from the northeast in the northern hemisphere and from the southeast in the southern hemisphere. Hadley maintained that the more intense solar heating in lower latitudes would lead to rising air in low and sinking air in high latitudes, whereupon equatorward moving air at low levels and poleward moving air at higher levels would be needed to fill the gaps. He then noted that in view of the earth's rotation, the air at low levels would soon move over a portion of the earth's surface that was actually moving more rapidly toward the east. The air would appear to be moving from the east with respect to the earth's surface; hence the trade winds. Similarly the returning air aloft would soon be moving from the west

with respect to the earth's surface, and, upon sinking, would become the prevailing westerlies of middle latitudes. Hadley's paper went almost unnoticed for many years, but by the early 19th century it had become the generally accepted explanation.

A feature of Hadley's argument was its purely qualitative nature. Taken at face value, the argument should apply equally well to the atmosphere of any rotating planet. Had observations of other planetary atmospheres been available, Hadley's argument would have been seen to be deficient. On Jupiter, for example, strong westerlies are observed in equatorial latitudes. Although one could argue that Jupiter may also possess trade winds far below westerlies, hidden by perpetual cloudiness, Hadley's ideas are inconsistent with the westerlies which are observed.

Hadley's theory eventually had to be rejected after new terrestrial observations showed that the surface winds in middle latitudes tended to be southwesterly (in the northern hemisphere) rather than northwesterly. Yet his reasoning still appeared sound. We now recognize that Hadley's assumed circulation pattern is only one of several dynamically possible patterns on the earth. It is not the pattern which the earth has chosen, evidently because of its instability, but it could conceivably be the circulation on some unknown planet.

The past century has been marked by an alternation of new physical theories offering dynamically possible explanations consistent with the most recent observations, followed by new observations showing that the new theories were wrong, or in need of modification. Today we feel that we understand the global wind systems fairly well, but we have also learned that physical reasoning, while capable of eliminating many proposed explanations of various phenomena, can seldom eliminate all but one. Meteorology is truly a science where adequate observations are a prerequisite for meaningful research and physical understanding, even when the research is purely theoretical.

How do the atmospheres of other planets enter this picture? We are interested in how the climate of various regions of the earth will change in response to various perturbations, such as a possible change in the direct solar energy, a change in global volcanic activity, which would increase the particulate matter in the atmosphere and alter the disposition of solar energy, or an increase in atmospheric carbon dioxide, resulting from the burning of fuels, which would redistribute the source of outgoing radiated energy.

Such changes resemble small-amplitude versions of the changes which one would encounter in passing from one planet to another. Solar heating is weak on Jupiter because of its great solar distance. Mars has dust storms far mightier than anything seen on earth. Venus has an atmosphere consisting principally of carbon dioxide. With adequate measurements of temperatures, winds, and clouds on the other planets, we can obtain an idea, independent of any theoretical speculations, of how the climate might respond to certain large perturbations. A first approximation to the response to small perturbations could then be obtained by interpolation.

A purely interpolative deduction might prove worthless because of the nonlinearity of some of the important physical processes involved. By a nonlinear process we mean, for instance, one where doubling the influence need not double the response; the response might increase manyfold, or not at all. The process of advection--the transport of a property of the atmosphere by the motion of the atmosphere itself--is a familiar nonlinear process in dynamical studies. The effect of dust, clouds, or trace gaseous constituents upon incoming and outgoing radiation is another. A cloud layer, for example, may reflect much of the solar radiation, but a layer twice as thick need not reflect twice as much radiation, and certainly cannot if the original layer was already reflecting more than half of the radiation received.

It is very difficult to assess the nature of nonlinearities by purely qualitative reasoning. Fortunately, a device which is especially well suited for dealing with nonlinearities is the computer. As a consequence, we understand a good deal more about many nonlinear processes than we did a generation ago.

One of the commonest approaches to the climate problem today is numerical modeling. A model is simply a system of mathematical equations representing the physical laws which govern the atmosphere and its surroundings (ocean, land, ice, vegetation, etc.), arranged for solution on a digital computer. Because modeling is quantitative and can keep track of the net effect of a collection of physical processes whose individual effects may tend to cancel, it is felt by many scientists to offer the most feasible approach to the climate problem. Certainly, with proper application, it can take the nonlinearities into account.

The systems of equations are regarded as models of climate rather than true mathematical descriptions because the physical processes which could conceivably be included are so numerous that it is virtually impossible to include them all, and a subjective choice of processes is needed. Moreover, many of the processes which are included are expressed in only approximate form.

It is common practice to formulate the approximations, when possible, so that the model correctly reproduces today's climate, when today's solar heating, volcanic activity, etc., are used as inputs. Unfortunately, this does not assure us that the appropriate change in model climate will accompany a given change in input. The sensitivity of the model to the input is more likely to be reasonable if the model reproduces today's climate for both winter and summer. However, if the input is varied so greatly that it becomes characteristic of another planet, a more severe test of the model is possible. If the model successfully reproduces both the terrestrial climate and that of another planet, some faith can be placed in it as a tool for nonlinear interpolation between such extreme states. A requirement, of course, is that the climate of the other planet be well observed. Planetary atmospheric studies thus have the capability of increasing the scope and usefulness of climate modeling.

Beyond these specific considerations, it would appear that one who typically thinks in terms of the atmospheres of the planets, instead of only that of the earth, is less likely to overlook some physical process

of true importance. Insights gained by considering processes in an exaggerated form in the atmosphere of another planet can alert us to the role of that process in the earth's atmosphere. Some examples of this type of interaction between studies of the atmospheres of the earth and other planets will be given in what follows. At best, we do not yet know what physical processes are essential and which are totally irrelevant to climatic change, although some processes are obviously more important than others. A process which can be shown to be clearly important for the climate of another planet should at least be considered potentially important for the earth.

It is a truism in science that purely theoretical research often, sometimes years later, finds a practical application. Even before the application is discovered, however, one can speculate intelligently as to the fields in which applications will likely occur. The chances are favorable that pure research in planetary atmospheres will find additional application in the problem of terrestrial climate change.

SECTION II

CURRENT STATE OF KNOWLEDGE

The planetary general circulation is the total response of the outer fluid layers of a planet to external forcing. Thus, in the case of the earth, we are concerned with the response not only of the gaseous atmosphere, but also of the underlying oceans. The elements of this response include the instantaneous weather (temperatures, winds, precipitation), the average weather or climate, and such other factors as ocean state, pollutant concentrations, soil moisture, snow and ice abundance, etc., which are affected by, and can themselves affect, the weather and climate. The description of this response requires knowledge of the composition of the atmosphere-ocean system, (gases, condensates, aerosols, sea-ice, etc.), its thermodynamic state (temperature and pressure), and its dynamical state (horizontal and vertical winds, ocean currents).

Understanding and predicting the response of the system to external forcing draws upon many branches of physics: fluid dynamics, radiative transfer, thermodynamics, chemistry, etc. The final test of our understanding comes in applying our theories to a variety of real situations. The earth's atmosphere, as we currently observe it, provides many such tests, but these do not cover the full range of circulations that have occurred and might occur under other conditions.

One convenient way of analyzing the response of an atmosphere to external forcing is to determine its energy cycle. Basically, atmospheric general circulations are driven by external heating, most commonly the radiative energy from the sun. Where this energy is absorbed in an atmosphere depends on its composition and structure. Spatial variations in the amount of absorption lead to temperature gradients which create pressure gradients and thus drive motions. From the point of view of the energy cycle, we can say that potential energy and internal energy are produced with a nonuniform distribution by the heating, and they are, in turn, converted into kinetic energy. The properties of the resulting motions will depend on the temperature structure. The motions may transport heat and thereby modify the temperature structure and in turn the motions themselves. Motions also can affect the composition of the atmosphere, for example, by leading to condensation and cloud formation. They can raise aerosols from the surface, thereby changing the absorption of radiant energy, and ultimately modifying the temperature structure and motions themselves. The kinetic energy is ultimately dissipated by small-scale processes, or converted back into potential energy, thereby again affecting the temperature structure and motions. Finally, the heat added to the system is balanced over long periods of time, by emission of thermal radiation to space. This emission is also controlled by the thermal structure and composition of the atmosphere and therefore is affected by all the processes mentioned above. Such feedback mechanisms make understanding of the general circulation of an atmosphere extremely difficult.

In view of the complexity of these feedback systems, and in view of the fact that our most powerful tools, computers and satellites, have only been available for a short time, it is not surprising that our understanding of the general circulation of planetary atmospheres is in a primitive state. Even in the case of the earth's atmosphere-ocean system, our understanding is far from complete. The problem of climate change is even more difficult. The average general circulation is not necessarily fixed, but may change both in response to slow changes in external forcing, such as changes in the amount of solar heating, or in response to slow changes of an internal nature, such as increases in the amount of carbon dioxide in the atmosphere. In this section we review the current understanding of some important factors in this complex feedback system in the broad context of the various planetary atmospheres. In doing so, no claim is made that all of the important areas are covered; rather, it is a selection of those topics which appear important to this group at this time.

A. GENERAL CIRCULATION

For the last several decades, a good description of the earth's atmospheric circulation in the northern hemisphere has been obtained through a network of pilot balloons and radiosondes. However, more recently, cloud-tracer motions obtained from geosynchronous satellites are improving the global description of winds. Similarly, temperatures aloft have been measured in the past by radiosonde networks, but they are now also being obtained by polar orbiting satellites, and in the future they will be obtained by geosynchronous satellites. The observations have defined the horizontal motions and temperatures of the atmosphere quite accurately. Adequate measurements of vertical motions are not yet available, but to a considerable extent these can be calculated from the other fields. These observations have fostered the development of a considerable capability for simulating the weather, but perhaps of even greater significance for the climate problem, they have led to a fairly detailed understanding of the cause-and-effect relationships between various elements of the atmospheric system. Nevertheless, much remains to be discovered.

The earth's climate depends sensitively on the temperature structure of the world ocean and hence, indirectly, on its circulation, but observations of oceanic circulation are comparatively scanty. We know little more than the gross features of the ocean's circulation. A few experiments, limited in space and time, have revealed detailed eddy structures at scales of the order of 100 km, but the distribution of such eddies, as well as their relationship to larger-scale features of the ocean circulation, remains obscure.

The Martian atmosphere has been the subject of more intensive satellite observations than any other planet besides the earth; even so, few direct observations of the atmospheric circulation are yet available. The Viking landers are providing valuable information on the winds and pressures near the surface at two locations, but data from two sites cannot define the global circulation patterns. A considerable amount of knowledge about the atmospheric temperature structure has been obtained from Mariner 9 and Viking radio occultation and infrared

observations. Although the time and space coverage is not yet adequate to define the mean atmospheric temperature structure accurately, a good start has been made and much quantitative information is now available on temperature distributions. On such a rapidly rotating planet, there is a useful approximate relationship between temperature gradient and wind, the thermal wind equation, and this allows us to infer a great deal about the horizontal motions from the observed temperature structure. As a consequence of these observations and inferences, we know that there is a large horizontal temperature gradient and strong stability with respect to vertical motion (static stability) in the winter hemisphere, much as there is on earth during winter. We know that atmospheric tides and gravity waves are prominent, and that global dust storms and meridional mass flow toward the condensing polar cap and away from the subliming cap are unique features of the Martian general circulation. We also know that eastward traveling weather systems, resembling those of terrestrial mid-latitudes, are characteristic of Martian middle latitudes during winter.

Virtually all our information relevant to Jupiter's circulations has been obtained from telescopic measurements of displacements of cloud features in its atmosphere. These have been extensively observed for a century, and as a result, the mean zonal motions in Jupiter's visual layers are fairly well defined. Virtually nothing is known about the other components of motion, although interesting meridional circulations are sometimes observed in the vicinity of the Great Red Spot. The most useful satellite observations relevant to the Jovian circulation are the high-resolution pictures of the cloud layers obtained by Pioneer 11. These pictures clearly reveal the presence of eddy structures and show a distinct change in the cloud patterns from low to high latitudes, which implies a fundamental latitudinal change in the nature of the circulation. Calculations based on the observed thermal infrared emissions yield information on mean temperatures and lapse rates in the visible layers, but very little is known about horizontal temperature gradients. Application of the thermal wind equation, in this case to calculate latitudinal temperature gradients from the observed zonal winds, gives some indication of the latitudinal temperature structure. Jupiter appears to be a planet on which circulation features are extraordinarily long-lived. Energy exchange over a very wide range of motion scales appears to play a central role in the Jovian general circulation. Release of latent heat may also be significant.

The circulation of the atmosphere of Venus has been observed from the earth as well as from spacecraft. Mariner 10 yielded good measurements of zonal motions and an indication of meridional motions in the upper part of the Venus cloud system. The Russian Venera probes measured velocity magnitudes in the lower atmosphere, but the global patterns of circulation in the lower atmosphere remain unknown. The vertical temperature structure has been determined in the upper atmosphere by the Mariner radio occultation experiments, and in the lower atmosphere by the Venera probes. Infrared observations and temperature measurements by the different Venera probes give an indication of the magnitude of the horizontal temperature variations but little is known quantitatively. The present body of data indicates that interactions between waves and mean flow play an important role in the general circulation. The reality of the 4-day rotation at cloud-top level is now generally

accepted, but experience with slowly varying zonal flow in the earth's tropics should caution us as to the permanence of this feature. Indeed, there are observational hints of time variations in this flow.

In large part, our understanding of the circulations and temperature structures of planetary atmospheres is still limited to an ability to predict some of their gross features. Such predictions may be based on simple scaling arguments which allow estimates to be made of the relative efficiencies of the heat transports by the motions and by radiation. For example, in massive atmospheres, where the meridional motions are relatively efficient, meridional temperature contrasts should be relatively small. In less massive atmospheres, where meridional motions are relatively inefficient, meridional temperature contrasts should be larger. Although such scaling arguments explain some of the gross differences between Venus, the earth, and Mars, we do not yet have sufficient information to know if the same sorts of estimates work for Jupiter.

More sophisticated understanding of the motions and temperature structure requires a greater amount of observational information than has been available for the other planets. In the case of the earth, the wealth of available data has formed the basis for detailed understanding of various components of the circulation and has also made it possible to carry out diagnostic calculations of quantities such as transports by large-scale eddies. It has allowed us to validate theoretical models which can be analyzed rigorously. For example, we know that the dynamical mechanisms which are primarily responsible for converting potential and internal energy to kinetic energy in the earth's atmosphere and which therefore exert a primary control on the temperature structure are moist convection with its associated latent heat release and instability associated with horizontal temperature gradients (baroclinic instability). However, many details of these processes, as well as of the interactions between the atmosphere and ocean, which are vital links in the climate system, are not yet fully understood. In regard to the atmospheres of Venus, Mars, and Jupiter, even less can be said. The processes of moist convection and baroclinic instability which are so important on the earth have not been positively identified in any other atmosphere although there are strong indications that baroclinic instability is important in the Martian atmosphere at least, and moist convection may be important on Jupiter. The differences in the external factors controlling the various atmospheres appear to be sufficiently great that the general circulation regimes of the atmospheres of Venus, Mars, and Jupiter are qualitatively different from that of the earth. Some of the important differences in the external factors have been identified. These include, in the case of Venus: the slow rotation rate of the planet and the great mass of the atmosphere; in the case of Mars: the pronounced surface topography, the small mass of the atmosphere, and the fact that the chief atmospheric constituent is subject to phase changes; and in the case of Jupiter: the great size of the planet, the lack of a solid boundary below the atmosphere, and the heating of the atmosphere from the planetary interior.

B. WAVES AND TIDES

Waves are a ubiquitous feature of fluid motion. They appear in a variety of forms on the earth where their scales range from that of ripples on a pond to atmospheric waves whose length is the circumference of the earth. We have good evidence that at least certain sorts of waves also exist in the atmospheres of the other planets, and while there seem to be many points of similarity to terrestrial waves, there are also obvious differences.

In what sense are waves important to the understanding of the general circulation of planetary atmospheres? For the earth's atmosphere, most of our theoretical understanding, usually a necessary antecedent to the ability to simulate, arises from the use of the concept of waves. Two classes of waves are most significant in planetary atmospheres: gravity waves, in which the wave-like character arises from the restoring force of buoyancy, and Rossby waves, in which flow perturbations undergo restoring accelerations as a consequence of the planetary vorticity field.

In general, atmospheric disturbances will exhibit both types of behavior, but they are usually dominated by one or the other. The wave concept has allowed very important progress to be made in understanding the stability and predictability of large-scale motions, the structure of atmospheric tides, the response of the flow to thermal or topographic forcing, the exchange of energy between scales, and the nature of interactions between flow perturbations and the mean flow. Thus, it is natural to ask: what is the evidence for waves in other planetary atmospheres, and what can we understand of the total dynamics of those atmospheres in terms of the wave concept?

The remarkable sequence of Mariner 10 ultraviolet images of Venus revealed some unexpected features in the cloud top structure. Several of these resemble waves, and have been described as "bow-like features," "circum-equatorial belts," and the planetary scale "dark Y." The "bow-like features" are suggestive of long quasi-stationary gravity waves, aligned mainly north-south, but curving, as the name implies; they are located immediately downwind of the subsolar point. The "circum-equatorial belts" suggest solitary gravity waves aligned east-west, while the "dark Y," a feature long noted in ground-based observations, may be a combined Rossby-gravity wave, although the unraveling of its character is now blocked by our lack of understanding of the cause of the dark ultraviolet markings. From a theoretical point of view, each of the several existing models designed to explain the 4-day rotation of the atmosphere at cloud-top level depends in some way on interactions between waves and the mean flow. What the nature of the interaction is and which of the existing models is correct, if indeed any model is, remains obscure.

Spacecraft orbiting Mars have observed banded cloud structures which are clearly identifiable as topographically forced gravity waves. They have also detected large-amplitude diurnal atmospheric temperature fluctuations identifiable as thermally forced tides. Temperature variations in the vertical atmospheric profiles measured by Viking and by the earth-based

stellar occultation technique, as well as Viking surface pressure measurements, reveal tides, and each type of observation provides illuminating information about their magnitude, structure, and forcing. There are good theoretical reasons to expect unstable Rossby waves in the sub-polar regions of Mars during winter, and Viking 2 meteorological data clearly reveals the presence of regular disturbances having some of the required properties. There has been considerable theoretical work on topographically forced Rossby waves on Mars, but evidence bearing on this problem is still skimpy.

Finally, on Jupiter, wave-like phenomena have been observed at the interfaces between the zonally aligned belts and zones. Because of the lack of high-resolution information or supporting data, little is known about these waves. Unstable Rossby waves have been theoretically predicted for Jupiter, but the alternating belts and zones might be a visible manifestation of an axially symmetric disturbance.

C. TOPOGRAPHIC FORCING OF CIRCULATION

In spite of the relatively small vertical extent of large-scale topography on the earth (no more than about $1/4$ of a scale height), significant perturbations of the general circulation are induced. Topography is important for slowly varying circulations such as the monsoon regimes, and for modifying the behavior of individual storms. In some regions such as in Southeast Asia in summer, the magnitude of the topographically induced circulation is larger than the larger-scale mean flow itself. Topographic features appear to perturb the mean flow by two mechanisms. First, they simply present an obstacle to the flow, thus causing both horizontal and vertical deviation of the motions. In the simplest case this will produce a train of downstream waves within the basic flow. An example of this feature in the large-scale flow may be seen in the lee-side trough east of the Rockies, which usually dominates the winter circulation of the North American continent. Topography also perturbs the general circulation by providing an elevated heat source to the atmosphere. The Tibetan Plateau in summer provides this kind of perturbation.

On the earth, differentiation between these two forcing mechanisms is extremely difficult, mainly because the elevated region may be acting both as deviator of the flow and as heat source. This dual role is not linear, as the mountain's role as an elevated heat source may depend upon its role as a flow deviator, a complication produced on the earth mainly by the hydrologic cycle. Without water and its phase changes, mechanical and thermal effects would be more separable. Then, in regions of strong insolation, where the mean winds are usually easterly and light, the mountains would act principally as an elevated heat source. In regions of small insolation, where the latitudinal temperature gradient is strongest, and the basic flow westerly, the mountains would act as deviators of the mean flow and would be capable of exciting strong wave response in the westerlies.

Some progress has been made in sorting out the relative roles of topography by studying the atmospheres of other planets. Mars is of particular interest in this regard, since it possesses topographic

scales of the same order as its atmospheric scale height. Since Mars does not have oceans or a significant hydrologic cycle, it is essentially a simpler system: one in which the two effects of topography are easier to separate.

The infrared spectroscopy of Mariner 9 has been extremely useful in providing the vertical temperature structure over elevated terrain. The data indicate that the topographic relief is imprinted into the temperature structure to great heights, providing a relative heat source for adjacent regions of the atmosphere. Such structure is indicative of an extremely rapid radiative or convective adjustment. Theoretical studies indicate that much of the circulation of Mars is driven or severely modified by this topographical effect. It is a dominant effect in the summer hemisphere and in low latitudes, coinciding with regions of strongest insolation.

On the other hand, in the Martian winter hemisphere, where insolation is small or negligible, theory and terrestrial experience suggest that topographic forcing should be almost completely in the mechanical mode. There, topography should act to deflect the strong basic westerly flow producing standing Rossby waves of nearly planetary scale downwind from the topographic source. Because the role of topography is exaggerated, Mars can provide a useful testing ground for the theory of topographic influences on flow as we continue to learn more about the actual circulation of that planetary atmosphere.

There is also topographic surface relief on Venus, which has been observed by radar, but the nature of its interaction with the circulation remains to be discovered along with a host of other processes in that planet's mysterious lower atmosphere.

D. PLANETARY BOUNDARY LAYERS AND DISSIPATION

Planetary boundary layers are those regions of the atmosphere near the surface which contain active convection or in which large vertical variations in frictional stress or heat flux occur. Kinetic energy dissipation in the earth's atmosphere occurs largely in the planetary boundary layer. The properties of these layers profoundly influence and are influenced by the magnitudes of the momentum, heat, and mass exchanges between the surface and the atmosphere. Since these exchanges provide the principal thermal and frictional drives for the terrestrial troposphere and since the dynamical behavior of planetary boundary layers is distinctly different from that of the regions further removed from boundaries, a substantial theoretical and empirical methodology has been developed especially for planetary boundary layers. Best developed are the similarity theories which have been extended to include influences of the coriolis parameter and the depth of the convective layer.

This approach is most complete and most successful under statically unstable conditions when there is a clearly defined convective layer depth. Fortunately, most vertical exchange occurs under such convectively unstable conditions so that this case is the most important one.

Recently, second-order closure theories, which yield more detailed answers and which reduce the level of empiricism, have been applied with some success. Both similarity theory and second-order closure theory contain major empirical elements, however, so that it is highly desirable to explore other planetary boundary layers in order to check the universal validity of these theories.

Mars, and possibly Venus, offers opportunities for such comparisons. Viking has provided a substantial body of knowledge about the Martian boundary layer. Surface winds and temperatures have been measured, boundary layer convective clouds have been imaged, and temperature profiles through the atmosphere have been obtained for both stable and unstable conditions. Preliminary analyses of these data are encouraging. Such boundary layer properties as the gustiness of the wind, the height of the convective layer, the difference between the ground and near-surface temperature, and the diurnal variability of the near-surface wind are all consistent with expectations based on terrestrial boundary layer theory. Thus far, the Martian data appear to support the universal applicability of this important theoretical structure.

At present, almost nothing is known about the boundary layer of Venus. The atmosphere appears to be nearly isentropic up to about 50 km. It is not known whether or not small-scale convection occurs in this region. Because net radiation (the difference between downcoming solar radiation plus infrared radiation and upwelling infrared plus reflected solar radiation) at the surface is small, the convective heat flux, which must balance the net radiation, must also be small, but this does not preclude the possibility of a deep, active convective layer.

To the extent that kinetic energy dissipation takes place in the interior of an atmosphere, it is more difficult to deal with. A significant fraction of the dissipation in the earth's atmosphere appears to occur in the free atmosphere, either in convective clouds, or in regions of strong shear of the horizontal wind. Although it is very difficult to establish the exact mechanisms and role of turbulent dissipation in the free atmosphere, any insights gained from studies of this process on other planets may be helpful to terrestrial dynamic meteorologists. This is particularly true of Venus and Jupiter, since dissipation in the free atmosphere is likely to be important on both planets.

E. CLOUDS, AEROSOLS, AND RADIATION

In addition to the gases comprising a planetary atmosphere, clouds and aerosols can play a vital role in the atmospheric energy cycle. Like the radiatively active gases, clouds and aerosols, by virtue of their scattering, absorption and emission properties, influence the total amount of energy deposited in the atmosphere, the energy reradiated to space, and hence the vertical and horizontal distribution of radiative heating and cooling. On earth, the moist convection process is driven by latent heat release, and latent heat may be dynamically important on other planets as well. These diabatic effects of clouds and aerosols

provide feedbacks which alter the character of the induced motions. In order to understand the energy cycle and dynamics of an atmosphere, we must know the distributions of gases, clouds, and aerosols, their optical properties, and their response to dynamics. Here we summarize current knowledge of these properties for the atmosphere of the earth, Venus, Mars, and Jupiter.

On the earth, the principal active radiating gases are water vapor, carbon dioxide, and ozone. Recently, the possible radiative role of such minor gaseous constituents as fluorocarbons has been recognized. In addition, clouds play a dominant radiative role in the troposphere, with aerosols playing a lesser but still significant role in both the troposphere and stratosphere. The terrestrial water clouds are composed of either liquid droplets or ice particles (or mixtures) ranging in diameter from about 1 to 100 μm depending on altitude and location. Aerosols over oceans are comparatively large ($\sim 1\text{--}10\ \mu\text{m}$) and are composed primarily of sea salt. Aerosols over land are smaller ($\sim 0.1\text{--}1\ \mu\text{m}$) and are composed primarily of soil, sulfur compounds and organic matter. The stratospheric aerosol is mostly sulfuric acid particles of submicron size.

If the atmosphere were in radiative equilibrium, it would have a statically unstable lapse rate up to 3-5 km and have a higher mean meridional temperature gradient (by a factor of three) than is observed. Differences between the radiative equilibrium temperature distribution and the actual one imply a differential heating distribution which drives motions in the form of vertical convection in the equatorial regions and in the form of large-scale quasi-horizontal motions in mid latitudes. A measure of the importance of radiative heating relative to transport by the circulation in determining the actual temperature distribution is the radiative time constant. This ranges from 20 days in the troposphere, where radiation acts more slowly than transport, to 5 days in the upper stratosphere, where radiation acts more rapidly than transport during summer.

Water clouds influence the atmospheric system in several important ways. Except for ice- and snow-covered surfaces, water clouds have the highest albedo in the earth-atmosphere system and therefore the approximately 50% cloud cover significantly raises the earth's albedo. The high infrared absorptivity and emissivity of water clouds normally tend to destabilize the temperature lapse rate in the cloud and may thus enhance cloud growth. The effect of the latent heat of water released by phase changes during cloud formation also enhances convective activity. Latent heat release provides the primary heat input to the atmosphere in equatorial regions where surface heating is converted to evaporating water over the oceans. This also provides the energy source for hurricanes.

On Venus the atmosphere is composed almost entirely of the radiatively active gas carbon dioxide. The high surface temperature (740°K) and amount of sunlight reaching the surface, as measured by the Venera spacecraft, strongly suggest that a greenhouse mechanism is at work in this atmosphere (which is about 90 times as massive as earth's atmosphere). That is to say that, although some solar radiation can penetrate

the clouds to heat the surface, thermal radiation is effectively blocked from escaping by the dense, cloudy atmosphere. Radiative calculations suggest that carbon dioxide alone may not be sufficient to cause this greenhouse effect. The observed water vapor and other minor constituents may, however, be capable of providing the required additional infrared opacity. The observed cloud layer is apparently horizontally uniform and composed of very small droplets of highly concentrated solution of sulfuric acid and water. Although far less dense, the earth's stratospheric haze layer has a similar composition. The radiation flux measurements made by the Venera spacecraft show that three quarters of the sunlight absorbed by Venus is deposited in this cloud layer. Thus, not only does Venus' cloud layer determine the planetary albedo and infrared emissivity, but it also controls the altitude of deposition of the solar energy in the atmosphere. Since sulfuric acid is transparent in the ultraviolet, the observed cloud contrast features, those forming the "dark Y," suggest the presence of some additional substance in the cloud. Such UV inhomogeneities raise the possibility of a strong dynamic feedback as a result of the differential heating associated with this contrast.

The atmosphere of Mars is 95% carbon dioxide, but with a surface pressure less than 1% that on the earth. Thick condensate clouds affect radiation exchange over the winter pole. The energy exchanges in the nonpolar regions of Mars, on the other hand, are determined primarily by the radiative properties of carbon dioxide and suspended dust; condensate clouds are relatively rare. Radiative energy exchange and transport of energy by the circulation are both important on Mars. The thin atmosphere is very sensitive to the amount of dust present in it. The dust absorbs visible radiation and absorbs and emits thermal infrared radiation, with the net effect of heating the atmosphere. There appears to be a powerful feedback loop between dust heating of the atmosphere and the consequent generation of strong winds. Dust heating of the atmosphere can be so intense that global dust storms are produced, and these radically change the atmospheric temperature distribution. One further intriguing feature of the condensate cycle on Mars that distinguishes it from the other planetary atmospheres is the fact that as much as 20% of its total mass condenses out at the winter pole during the Martian year.

The atmosphere of Jupiter will prove to be one of the most challenging to understand because it is composed not only of several radiatively active gases (hydrogen and traces of methane, ammonia, and water), but it also contains several cloud layers. The visible, upper cloud layer is composed of ammonia ice, but the infrared emissions from Jupiter suggest the presence of one or two more cloud layers below. Radiative equilibrium calculations also suggest that the visible atmosphere must be convective in its lower regions, and that clouds will form within this convective lower portion of the visible atmosphere. Some current theoretical models of the large-scale circulation of the Jovian atmosphere hypothesize an important role for latent heat release. If this is in fact the case, studies of Jovian cloud dynamics may provide particularly helpful clues to some terrestrial cloud dynamics problems.

F. CHEMISTRY

Planetary climates are subject to change when perturbations occur in the radiation budget of the atmosphere and surface. Thus, chemical reactions can directly influence atmospheric dynamics by altering the concentrations of the absorbers of solar and thermal radiation which govern the local radiative heating rates and the radiation budgets. On earth, for example, studies of the ozone layer have demonstrated the role of ozone chemistry in thermal forcing of the upper stratosphere and mesosphere and in damping of atmospheric waves. Recent theoretical work suggests that the structure of planetary waves, even in the troposphere, may be sensitive to the thermal structure of the stratosphere. It is also possible that thickening of the stratospheric sulfuric acid cloud layer could result from increased injections of SO_2 through volcanic activity or through burning of high-sulfur coal. Recently it has been found that COS, another possible product of volcanic activity or combustion, is present in the lower stratosphere. Such a thickening could alter the planetary albedo and thus perturb climate. The analogy with the sulfuric acid cloud which completely shrouds the very hot surface of Venus is evident.

Another well-known example is the increase in atmospheric CO_2 which has resulted from burning of fossil fuels over the last century. The CO_2 concentration is modulated by reactions with ocean water and sedimentary carbonates. However, oceans are not present on Venus or Mars. The stability of Martian CO_2 is accounted for by catalytic reactions involving dissociation products of water. This chemistry bears a close resemblance to the chemistry controlling the ozone concentration near the terrestrial stratopause. Even perturbations to chemical cycles which result in alterations in the concentrations of very minor gaseous constituents can be significant in perturbing the planetary energy budget. We have already alluded to the fact that the fluorocarbons, for example, may play a significant role by absorbing energy in the "window" regions of the earth's infrared spectrum where the major atmospheric absorbing constituents are essentially transparent. It is also worth noting that a major product of the decomposition of the fluorocarbons in the stratosphere is HCl. This gas has been detected on Venus, but with mixing ratio 1000 times greater than that found in the terrestrial stratosphere, and the analogies between chlorine chemistry on Venus and the earth have provided some valuable insights.

The gas-to-particle conversion reactions which produce condensation nuclei affecting cloud formation may also influence climate by altering the precipitation efficiency of clouds. On Venus, gas-to-particle conversion is central to understanding the nature of the clouds. We may expect that studies of this process in the Venusian context will enhance our understanding for the earth. There is even a possibility, still highly speculative, that gas-to-particle conversion may affect the sensitivity of cloudiness to variable components of solar radiation. The infrared albedo of Neptune has recently been observed to increase substantially, presumably due to a dramatic change in cloudiness. Understanding the chemical and physical processes leading to this remarkable change in climate on Neptune could conceivably provide some insight

into the sensitivity of the earth's hydrological cycle to external influences.

Chemical processes in planetary atmospheres are often strongly influenced by atmospheric motions. Studies of CO₂ photochemistry on Venus and Mars, of sulfuric acid cloud formation on Venus, and of H₂, CH₄, NH₃, and CO chemistry on Jupiter have resulted in estimates of vertical mixing rates in atmospheres under varying dynamical conditions. On earth, studies of CH₄, fluorocarbon, and N₂O photochemistry have provided similar information for the stratosphere. Except in the planetary boundary layer, vertical transport, particularly on the smaller scales, is a poorly understood phenomenon. The existence of the special laboratories provided by the other planets should prove most useful in furthering our understanding of this problem.

G. PAST CLIMATES

It is conceivable that the planets may hold decipherable evidence of past climates, and that they may thus provide clues to mechanisms of climate change. We should not be too optimistic about this prospect, if we bear in mind the extreme difficulty of unraveling even the earth's past climate history, but such possible clues should not be ignored.

At the present time, Mars appears to offer the best indications of climate change. Much of its surface has been swept by massive erosion in the rather distant past. Many of the erosional features resemble channels, and these are widely believed to be indicative of large amounts of running water in the past. Whether they are due to water erosion or not, the channel features imply powerful atmospheric processes which are not occurring at present. A second suggestive class of features is the layered terrain of the polar regions. The layers are of relatively recent origin, and they appear to indicate episodic deposition of dust and/or condensates at the poles. They include both regular layered structures and unconformities, suggesting that climatic variations on at least two time scales have occurred.

We still know too little about the surface of Venus to draw inferences about past climates, but earth-based radar images show abundant large craters suggesting that at least parts of the surface retain the imprint of a very early period in solar system history. Consequently, there is every reason to expect that the surface morphology does hold clues to past climates on Venus.

SECTION III

OUTSTANDING QUESTIONS

In this section, we discuss some of the gaps in our knowledge of planetary atmospheres other than our own. These gaps need to be narrowed if knowledge of the planets is to contribute to greater understanding of atmospheres in general and of that of the earth in particular.

A. GENERAL CIRCULATION

Perhaps the most basic question we might pose regarding a planetary general circulation is: What is its form? That is, what are the distributions of the mean winds, and how are they related to the pressure and temperature fields? We should also include the question of the character and distribution of the large-scale variability in these quantities. But an understanding of atmospheric processes only comes when we obtain answers to a second basic question: What are the mechanisms by which the general circulation is maintained? In other words, what are the causal connections between the various components of the general circulation, and between these components and the boundary and driving conditions of the atmosphere? Advance of the science requires more than the capacity to simulate some of the causal connections; it also requires a capability for conceptualizing them in relatively simple terms. Thus, for example, the development from L. F. Richardson's early unsuccessful forecasting experiment to modern numerical weather prediction required more than the invention of computers; it also required the elucidation of the role of vorticity in atmospheric dynamics and the development of a theory of baroclinic instability. These concepts were needed in order to understand what it was that had to be simulated. Thus we may view the study of planetary general circulations and the study of the climate problem, in part at least, as searches for new concepts and for the range of applicability of existing concepts.

From this point of view, there are large differences in the present position with respect to Mars, Venus, and Jupiter. We have seen that the broad shape of the general circulation of Mars is known, at least in terms of the mean thermal wind. More information is needed on the distribution of mean surface winds and the meteorological variations of surface pressure, and, although we know something about the variability of winds and pressure, more data are needed in order to define the time and space distributions of variability and its structure. Enough is known to suggest that the concepts of tides and unstable Rossby waves apply to Mars. But the interesting question of the modifications to these concepts that Mars will force upon us remains. To what extent, for example, can we relate the general circulation of our earth-like neighbor to the general circulations observed and theoretically interpreted in laboratory rotating-dishpan experiments? Two new concepts appear to be emerging in the Mars data. First, Mars exhibits a highly coupled dust-heating-wind feedback system exemplified by the global dust storms. We would like to have a clearer understanding of the mechanisms of initiation, growth, and decay of these storms. A second concept is that of circulation driven in part by polar cap condensation and sublimation, but the degree to which this

process controls the gross form of the general circulation remains to be discovered.

In the case of Venus, only the broadest outline of the flow at the cloud-top level is known, together with a handful of measurements of one component of wind at depth and a handful of vertical temperature profiles. Thus, the pressing questions still deal with the gross form of the general circulation. We need to know the distributions of mean zonal and meridional winds between cloud-top level and the surface and the relationships between these distributions and the temperature field. Knowledge of variability is also needed. Are there time variations of the zonally averaged zonal and meridional winds? What are the amplitudes and what are the structures of the large-scale waves, those on the scale of the "dark Y" ultraviolet markings? What is the nature of the smaller scale waves? Presumably, these questions will be answered first at cloud-top level, and only much later in the interior, although wave concepts may allow us to draw significant inferences about the interior structure from a relatively few measurements. Conceptually, we would like to know how waves and the mean flow interact to maintain the 4-day rotation.

The Jovian situation is even worse in the sense that we do not even know the bounds of the region in which we can meaningfully discuss a general circulation. It is often tacitly assumed that the atmosphere above the cloud tops and for a few scale heights down from the cloud tops can be considered as an entity whose dependence on the deeper atmosphere can be described in terms of relatively simple boundary conditions. This would be a situation somewhat analogous to the relationship between the terrestrial thermosphere and the regions below. The dynamical drives and the physical processes in the thermosphere are sufficiently distinct from those below that, to a first approximation, it can be treated as a separate entity. On closer inspection, however, it appears that certain aspects of thermospheric structure are sensitive to details of dynamical processes at lower levels, and a similar situation may occur on Jupiter. Thus, a fundamental question concerns the degree to which the accessible part of the Jovian atmosphere can be treated as a dynamical entity. To what extent, for example, does the oceanographic concept of a "level of no motion" apply to Jupiter? (A similar question could be asked of Venus.) The answer to this question may be a long time in coming; in the meantime, much can be done to define the shape of the circulation at and just below the cloud-top level. The pressing needs here are to identify wind systems at smaller scales than those which have been defined thus far, to begin to obtain information on their vertical structures, and on their time evolution. The qualitative distribution of large-scale vertical velocity is defined by the cloud structures, but quantitative information is needed as well. These two types of information would help to define the nature of energy exchange between scales as well as the most important modes for conversion of potential and internal energy to kinetic energy near the cloud-top level.

B. WAVES AND TIDES

The preceding discussion illustrates the relationships between the problems of the general circulation and of atmospheric waves. But there are some specific questions concerning the observations and theory of

waves in planetary atmospheres which are worth special mention. First, note that only on Mars have waves been revealed by evidence other than their visible structure in cloud fields. There is a need for other kinds of data capable of revealing waves: e.g.: distributions of horizontal and/or vertical wind and/or temperature structure. Either sophisticated remote sounding techniques or in situ probes will be required to obtain these kinds of data.

For the Venus atmosphere, it is clearly crucial to obtain an understanding of the cause of the ultraviolet contrasts which reveal the waves. We also need to better know the kinematic characteristics of the waves: their propagation speed, wave lengths (both horizontal and vertical) and, perhaps most importantly, the circumstances under which the various waves arise. In addition, an effort should be made to observe and measure the tides driven by solar heating since these waves may play an important role in driving the zonal flow.

We have already noted the need for more global coverage on Mars to better define the distribution and structure of a variety of motion systems, including tides and Rossby waves. Observations of the temperature structure of the middle Martian atmosphere (25-80 km), with adequate horizontal and vertical resolution, may be able to determine the height at which vertically propagating waves degenerate into turbulence. Additional observations of vertical and horizontal temperature distributions are needed to define the structure of planetary-scale Rossby waves and to assess the importance of transport by these waves to the general circulation.

Since wave activity influences and is influenced by the mean zonal flow and mean static stability, better definition of the horizontal and vertical variation of the basic states is needed to understand the wave processes, particularly in the cases of Venus and Jupiter. Our experience with Venus demonstrates that this is not an easy task, but the strong interaction of waves and mean flows is a fundamentally important process in all planetary atmospheres, including the earth's upper atmosphere.

In investigating other planetary atmospheres, theoretical techniques and some insight into fundamental processes are developed which can be applied to terrestrial problems. From both terrestrial experience and indications from other planets, it seems clear that present theories of atmospheric waves need to be extended to include

- (1) More complicated basic states (e.g., vertically and horizontally varying basic flows).
- (2) Strongly nonlinear aspects of the waves (e.g., advection, degeneration into turbulence).
- (3) Different distributions of forcing (e.g., internal heat source on Jupiter).

Concepts and insights which have been developed in studies of waves in the terrestrial atmosphere have been applied fruitfully to investigations of other planets.

C. TOPOGRAPHIC FORCING OF CIRCULATION

Some insight into the influence of topography on the circulation of earth's atmosphere has already been gained by studying observations of the atmosphere of Mars and by subsequent model development. However, a number of related problems still remain which can benefit from further and more detailed investigations of Mars.

The first-order question is: To what extent do our theoretical concepts of the structure and amplitude of topographically forced planetary waves pertain to actual Martian conditions? Mars can be thought of as a testing ground for traditional theories of topographic forcing and for the vertical and horizontal propagation of forced waves. Further observations may reveal failures of these theories whose eventual resolution can lead to new or revised concepts. On the other hand, the theories may be shown to work well, in which case our confidence in their range of application will be enhanced.

A vexing aspect of the topographic problem could conceivably be illuminated by detailed meteorological observations at Mars. The dynamical effects of extremely steep slopes such as those of the Andes or the Tibetan plateau (slopes $\geq 1:100$) are not well understood and are difficult to model. Mars topography is characterized by slopes at least as great as those on earth and altitude variations that are much greater than those on earth. Since the Mars atmosphere is a simpler system, insight could be gained by studying it as an earth analogue. To accomplish this, an observational study would be needed to provide vertical structure information on spatial scales small enough to resolve the topographic structure and on time scales small enough to resolve diurnal variability. Ideally, such observations should also encompass seasonal variation.

D. PLANETARY BOUNDARY LAYERS AND DISSIPATION

The time scales and the modes of dissipation of kinetic energy are fundamental to the understanding of planetary atmospheres. Two examples illustrate this. A recently developed general circulation model does appear to simulate some of the most striking features of the circulation of Venus, including the 4-day rotation, but the steady state balances achieved in the model depend significantly on parameterized small-scale transports and on parameterized dissipation. Very little is known about motions at scales smaller than the planetary scale itself. Thus, first-order dynamical questions for Venus include: (1) What scale and modes of motion below the planetary scale actively transport heat and momentum vertically and horizontally? (2) What is the time scale for dissipation of the kinetic energy of the large-scale motions? (3) How is this dissipation accomplished? (4) Where does the dissipation occur in the atmosphere?

As a second example, an extension of a terrestrial general circulation model has been applied to Jupiter with very suggestive results, in that features similar to the observed belts and zones are developed by the model. But these results depend on the assumption of very low dissipation rates. The obvious question is: Does kinetic energy dissipation actually

take place at very slow rates (time scales of the order of years)? If not, one must conclude that such persistent large-scale features as the Great Red Spot are directly forced. If dissipation is so slow, the next question is why? This question cannot be answered without knowing something about the mode by which energy is transferred from the observed large-scale features to the small scales at which dissipation takes place.

The situation with Mars is somewhat different. It is quite possible that on Mars, as on the earth, much or most of the dissipation takes place in the planetary boundary layer. Since boundary layer theory is well developed it would be a particularly agreeable situation if it could be extrapolated to Mars. This would mean that terrestrial circulation and climate models could be applied to Mars without the addition of *ad hoc* free parameters to describe dissipation. Since most heat input processes can be modeled in a relatively straightforward way without the use of free parameters, Mars could then be used to test models with considerable confidence. Thus the questions for Mars are: (1) Is it correct that terrestrial planetary boundary layer theory can be extrapolated to Mars? (2) Does most of the dissipation of kinetic energy in the lower atmosphere take place in the planetary boundary layer? These questions can be checked by comparison of the results of general circulation models applied to Mars with more detailed observations of the present Mars climate.

E. CLOUDS, AEROSOLS, AND RADIATION

In order to understand the weather and climate of a planetary atmosphere, we must determine the influence on the radiation and dynamics of atmospheric gases, clouds, and aerosols. For example, even on the earth, with our extensive base of observations and theory, lack of understanding of the complicated physical interactions which control aerosol properties, and which influence the cloud structure and the radiation field, remains a fundamental obstacle to understanding climate. The effects produced by clouds and aerosols depend on several properties: their composition and microstructure (size, shape, and number density of particles), the gross structure of individual cloud or aerosol systems, and their spatial and temporal distribution. We must also study those microphysical processes which determine the composition and microstructure of the cloud and aerosol particles and those which govern their interaction with atmospheric motions. A bonus derived from understanding these properties of the atmospheric gases, clouds, and aerosols is that we can then use radiation as a more precise tool for probing the structure of the atmosphere, using clouds and aerosols to help in tracing or indicating circulation. This section outlines some problems in this area that should be addressed.

Since the cloud layer in the upper atmosphere of Venus so completely dominates the heat budget of the atmosphere, an accurate description of the cloud radiative properties is required. Information is needed on the composition, microstructure, and the horizontal and vertical distribution of the cloud. This could be used to determine the optical properties of the cloud, especially the identity of the ultraviolet absorber, and hence, the vertical and horizontal distribution of heating and cooling. The nature of the interaction between circulation and the cloud physical and chemical processes could then also be identified.

For Mars, there are three major problems, each associated with a distinct season, that must be addressed. The cloud physics as well as the dynamics of the condensation of the major atmospheric constituent, carbon dioxide, is a novel problem in planetary atmospheric science. It requires theoretical work on the condensation of a gas under conditions in which diffusion is not a factor limiting the growth of cloud particles. It also requires observation of the atmosphere over the winter pole of Mars to determine the dynamics of formation of carbon dioxide clouds. The cycle of water vapor on Mars is still mysterious. The factors controlling its exchange with the surface and polar caps and its transport within the atmosphere need to be delineated. Water vapor appears to control Martian ozone through a series of catalytic reactions, and coordinated observations of water vapor and ozone are needed to fully characterize this process. Finally, additional observations of the origin, growth, and decay of the global dust storms, as well as the properties of the dust itself, are required in order to understand the occurrence of these spectacular storms.

So little is known about the Jovian atmosphere below the cloud tops that almost everything remains to be learned. However, to start, the composition and vertical structure of the cloud layers and the cloud-forming gaseous constituents need to be known in order to perform the radiative-convective equilibrium calculations which are an essential first step toward useful models of the weather and climate. It is particularly important to determine whether or not massive water clouds are present below the visible ammonia ice clouds. For both Venus and Jupiter, there is a significant gap in our knowledge of the atmospheric composition in this respect. In particular, the atmosphere below the clouds should be 1% water by mass, if Jupiter's mixture of elements is like that of the sun. Dense clouds, heavy rainfall, and large release of energy should then be occurring near the cloud base. Observations from earth seem to imply only 0.001 as much water as a solar composition mixture. These observations refer only to small cloud-free areas where water may have been precipitated out, but they serve to exemplify our ignorance in such observational areas. Information on the vertical distribution, the horizontal homogeneity or inhomogeneity of the radiation budget, and the temperature in the subcloud layers is needed, and in order to understand the microphysical as well as dynamical processes occurring in these clouds, it is necessary to determine whether the belts and zones are continuous or broken stratified cloud areas or whether they are convective clouds. The only observations of atmospheric motions in Jupiter's atmosphere are from the tracking of cloud features. The interpretation of these cloud velocities as real winds could be seriously in error and needs to be re-examined in light of information regarding the structure of the visible clouds and how they might form, dissipate, or change shape with time.

F. CHEMISTRY

The most important input to studies of atmospheric chemistry is, not surprisingly, a detailed knowledge of atmospheric composition including even very minor constituents. The importance of good knowledge of the composition in the interpretation and understanding of dynamical processes has appeared repeatedly in the preceding sections. For the planets, earth-based spectroscopic observations from ground-based telescopes, aircraft,

balloons, and small rockets have provided some information. Mass spectrometers on Viking I and II and on the Pioneer Venus main probe have or are about to provide much more detailed data at least for the lower atmospheres of Venus and Mars. In fact, the only fully satisfactory method for measuring composition appears to involve the use of such entry probes or landers. Studies of the upper atmosphere of Venus and of the atmospheres on all the major planets and Titan are presently hampered by a lack of sufficiently detailed compositional data. We will ultimately want entry probes into all these planets.

Another necessary input to further studies consists of laboratory measurements of the rates of many poorly quantified but crucial reactions involved in planetary atmospheres. Of particular interest for Venus and Jupiter are a number of reactions involving sulfur compounds, hydrocarbons, and phosphorus compounds. Reactions of gases adsorbed on mineral surfaces appear to be of considerable importance on Mars and in desert areas on earth. Reactions involving electrons and ions are important in the upper atmospheres and ionospheres of all planets and also in the rarefied atmosphere of Io. Although there have been very large recent advances in our knowledge of atmospherically relevant reaction rates, more laboratory work on kinetics will be needed.

Finally, the continued development of a hierarchy of chemical models beginning with simple 1-dimensional chemical-diffusive models and ultimately leading to 2- or perhaps 3-dimensional models which contain the important chemical-radiative, radiative-dynamical, and dynamical-chemical interactions will be needed to help focus questions and to provide answers concerning the influence of chemistry on the dynamics and climate of the planetary atmospheres.

G. CLIMATE CHANGE

The questions of planetary climate history necessarily focus on Mars, the only planet on which possible indications of past climate have been observed. Specifically, we may ask: (1) Were the channel features produced by running water? (2) If so, was the water due to a past moist climate or some other process? (3) If due to past moist climate, when did it occur? These questions appear to require in situ and in depth geological and geochemical exploration of a typical channel. The last question requires that some absolute ages of a few samples of Martian material be obtained, so that ages of the channels can be derived by relative techniques such as crater counting.

With regard to the layered polar terrains, the fundamental question is: What is the depositional and erosional history of these features? If this can be established, the connection or lack of it with orbital variations will become clear, and more far-reaching interpretations of Mars' past climate history should follow directly. This would be particularly pertinent to understanding some of the features of climatic variation on earth which may be associated with long-term changes of orbital obliquity. The obliquity variation of Mars is much larger than that of earth and should have a more pronounced effect. It is even possible that the history of climate fluctuations recorded in the laminated terrain of Mars correlates with that of the

earth. Such correlation might indicate solar variations as the most likely cause of these climate fluctuations.

Establishment of the history of these Martian features is difficult, but, with some luck, it should be possible with a feasible rover. For example, a rover traversing a significant stretch of laminated terrain could establish dimensions, depths, and compositions of the layers, provide a detailed description of unconformities, and measure the current rates of dust fall, condensation, and sublimation. Such data might well be sufficient to establish a fairly detailed depositional and erosional history. It should be borne in mind that the interpretation of these features in terms of climate may be relatively straightforward because of the absence of the complicating effect of liquid water during at least the last billion years of Mars' history.

With regard to Venus, the first-order question is: Does the surface morphology retain clues to past climates? Imaging of the surface by radar is an experiment of prime interest to geologists, but the Martian experience has taught us that such an experiment is of great interest to the atmospheric scientist as well.

SECTION IV

MODELS AND OBSERVATIONS FOR PLANETARY ATMOSPHERES

One of the most common methods used to understand any phenomenon is to construct models and compare their predictions with observation. Modeling of the earth's climate has involved a hierarchy of mathematical models. These range from global-average radiation calculations, through linearized dynamical models and zonally or regionally averaged models with highly parameterized physical processes, up to "general circulation models" (GCMs) which explicitly include many interactive physical processes in their three-dimensional and time-dependent calculations. The simpler models are primarily for studying individual climate mechanisms in relative isolation, while the more explicit models simulate the climate system more completely and realistically. It seems clearly appropriate to extend this hierarchical modeling approach to other planets. A number of models of varying complexity have already been applied to the study of planetary climates.

For the simpler models, calculations have primarily been of the "radiative-convective" type. It may be useful to build on the considerable experience from earth climate modeling with zonally averaged energy balance climate models by extending these kinds of models to simulations of other planetary climates. In particular, seasonal simulation of the Martian climate, and perhaps even of changes in it associated with variations in orbital elements, appears to be a promising area for zonally averaged model studies of comparative planetary climatology.

It is conceptually useful to envision the development of a climate model applicable to all planets, as the final step in the hierarchy of increasing generality. Different general circulation models ultimately should not be necessary to simulate the climates of the different planets; in the ideal situation, the same GCM could be used for all planets, with only the prescribed external parameters being changed. Then variations in the results of applying the model to different planets would be associated only with the parameter changes, not with changes in model structure. It is in this spirit that the same GCM has been used to simulate and compare the atmospheric general circulations of the earth and Mars. Similarly, a simple quasi-geostrophic model, much like one used originally for simulation of the earth's general circulation, has been used to simulate some of the important features of the general circulation of Jupiter.

In order to be most useful for comparative planetary climatology, a GCM should be of maximum generality with a minimum of ad hoc compromises for a given planet. For example, the same numerical scheme for surface topography should be used, one which will be equally suitable to the surface topography of Mars, or of the earth. Similarly the same planetary boundary layer parameterization formulation should be used, one that is capable of forming the boundary layer of the earth as well as the deep ones that may develop in the atmospheres of Mars or Venus. Also, such a GCM should have convective and layer cloud parameterization schemes, including the cloud-radiation interaction processes, of such

generality that they will produce the clouds of different composition and structure appropriate to the prescribed chemical composition and orbital parameters of the different planets. The same generality should also hold for the photochemical processes in the GCM. This is a useful goal to have in mind, although the actual construction of such a model may not be practicable for some time.

One critical requirement for climate model development is an adequate observational data base. Observations serve the purpose of identifying and defining the important processes and their effects on the atmospheric state. The space-time distributions of winds, temperatures, pressures, heat balance components, and variations in composition also serve to verify the output of models.

The external parameters of planetary atmospheres -- gravity, radius, rotation rate, and orbital parameters -- are well known for the planets discussed here. However, not even these quantities are certain for the planets beyond Jupiter. The quantities which describe the state of an atmosphere are principally composition, pressure, temperature, and wind. Additional important quantities describe properties of solid surfaces (composition, albedo, topography) and of clouds and aerosols (composition, density, particle size distribution). A complete observational program for planetary atmospheres which would measure all of these quantities as functions of space and time is not practicable, but like the completely general GCM, it is a useful ultimate goal to keep in mind.

Here we try to identify those observations that are central to the modeling problem and to verification of theory based on the understanding outlined in Section II and the questions raised in Section III. This list is not intended to be "complete," but it does include those measurements which seem likely to lead to substantial gains in our understanding of these atmospheres.

The status of our current knowledge of the values of the observed properties of the planetary atmospheres is suggested by Table 4-1. We have not attempted to assign priorities or to specify accuracy requirements for these observations.

We now address some general observational goals for Venus, Mars, and Jupiter, list some specific observations required to achieve these goals, and identify scientific problems which these observations can help us to attack.

A. VENUS

Four general observational goals for the Venus atmosphere are:

- (1) To determine, more completely, the vertical and horizontal distributions of radiative heating and cooling, and the relationship of radiation fluxes to clouds,
- (2) To define a mean atmospheric state, including the large-scale mean wind distribution,

Table 4-1. Status of Observational Data Requirements for Mathematical Models of Planetary Atmospheres

Parameter	Venus	Earth	Mars	Jupiter
<u>General</u>				
Size, surface gravity, rotation vector and orbital parameters	1	1	1	1
Incident sunlight	2	2	2	2
Internal heat flux distribution	1	1	1	3
<u>Composition</u>				
Mean gaseous composition	2	1	1	2
Total atmospheric mass	1	1	1	2
Volatiles* on/in soil	3	2	3	4
Clouds* and aerosols*	3	2	2	3
<u>Surface Properties</u>				
Large-scale topography	3	1	1	4
Small-scale roughness	3	2	3	4
Soil thermophysical properties	3	2	2	4
<u>Model Verification Requirements</u>				
Pressures	3	1	2	3
Temperatures	2	1	2	3
Winds	2	1	2	3
Heat budget components	3	2	2	3

- Key: 1. Present information already adequate for the purposes of identifying all important atmospheric processes and defining their time and space distribution.
 2. Useful information available, but not adequate in the above sense.
 3. Little or no data available.
 4. Not applicable.

*Data on distribution and radiative properties of volatiles, clouds, and aerosols are needed for those models in which these variables are prescribed as input rather than calculated as output.

- (3) To define the smaller scale and transient wind systems, and identify their mechanisms,
- (4) To discover whether clues to past atmospheric processes are imprinted in the surface.

Specific observations required to achieve these goals include the following:

<u>Observation</u>	<u>Purpose</u>
Composition of the atmosphere	Goal 1, 2
Albedo and composition of the surface	Goal 1, 4
Composition, microstructure, horizontal and vertical distribution of clouds and aerosols	Goal 1
Radiative flux divergence	Goal 1
Pressure and temperature as function of location and time	Goal 1, 2, 3
Winds as function of location and time by direct measurement or by cloud motion analysis	Goal 1, 2, 3
High-resolution radar imaging of the surface	Goal 4

Some of the specific problems of the Venus atmospheric circulation, which these observations will help us to begin to solve, are the determination of the role of clouds in maintaining the greenhouse effect, determination of the role of dynamic heat transports in maintaining the observed temperature structure, and identification of the process which maintains the four-day wind in the upper atmosphere. We recognize that the Venus Pioneer will contribute significant observations in these areas, but it will not fill all important observational gaps, particularly in the areas of cloud microstructure and winds.

B. MARS

Three general observational goals for the Martian atmosphere are:

- (1) To verify or refute the predictions of current dynamic models,
- (2) To refine our knowledge and understanding of polar and dust storm processes,
- (3) To determine the paleoclimate of Mars.

The required specific observations are listed.

<u>Observation</u>	<u>Purpose</u>
Winds as function of location and time	Goal 1, 2
Pressure and temperature as a function of location and time	Goal 1, 2
Polar cloud composition, vertical motions and horizontal distribution,	Goal 2
Composition, microstructure, and variability of dust	Goal 2
Atmospheric aerosol loading as function of location and time	Goal 2
Distribution of water vapor as function of horizontal and vertical coordinates and time	Goal 2, 3
Geological sampling of polar regions	Goal 3

These observations will help us to understand the role of topography in the general circulation of a planet, the relationships between the structure of Rossby waves and the mean flow, the complex interaction of dynamics and phase changes occurring at the poles and its role in Martian weather and climate, and the role of the variation of the latitudinal distribution of solar insolation in determining the change of climate. Mars not only serves as an example of a planet with more extreme variations in its spin and orbital parameters than the earth but it also serves as a check on the long-term variability of the sun once the role of these parameters in producing long-term climate fluctuations on the earth and Mars is understood. The Viking data analysis is still underway and can be expected to yield additional data relevant to goals 1 and 2. Even so, much will remain to be done, particularly with respect to goal 3.

C. JUPITER

Three general observational goals for the Jovian atmosphere are:

- (1) To determine the rates and the vertical and horizontal distributions of heating and cooling and the relative importance of the solar and internal heat sources at different levels.
- (2) To determine the mean state of the atmosphere.
- (3) To determine the structures of the cloud and motion fields over a broad range of scales and at depths below the cloud tops.

The required specific observations are listed.

<u>Observations</u>	<u>Purpose</u>
Composition of atmosphere	Goal 1, 2
Radiative flux divergence	Goal 1, 2
Composition, microstructure, horizontal and vertical distributions of clouds and aerosols	Goal 1
Pressure and temperatures as functions of location and time	Goal 2, 3
High-resolution imaging of cloud motions and structures	Goal 3
Probe measurement of winds below cloud tops	Goal 2, 3

With these observations, we can begin to investigate the physical processes by which the heating of the Jovian atmosphere by the sun and the internal heat source is converted to kinetic energy of the winds, the processes by which these motions are organized into the symmetric cloud bands, and the processes which maintain the giant cloud features, the largest of which is the Red Spot. The Voyager missions will provide valuable initial data, and a follow-on Jupiter Orbiter-Probe mission would obtain the first *in situ* measurements of composition, temperature, and cloud structure. Both are obviously important steps along this path.

In addition to the above observations, many crucial properties of the atmospheric constituents of each of these planets are not adequately known. Therefore, laboratory work is needed to determine the following:

- (1) The temperature dependence of the heat capacity of CO_2 .
(This is needed to determine more precisely the static stability of the lower atmosphere of Venus.)
- (2) The temperature and pressure dependence of radiative properties of CO_2 .
- (3) The condensation physics of major atmospheric constituents.
- (4) The properties of hydrogen and helium at high temperatures and pressures.
- (5) The chemical reaction rates involving sulfur compounds, hydrocarbons, phosphorus, and the strong acids and water in both the gas and liquid phases.

SECTION V

IMPLICATIONS FOR EARTH CLIMATE RESEARCH

As has been stated earlier, the conditions and factors affecting the earth's climate are not replicated on other planets but the physical processes themselves are universal and are therefore subject to comparative study. This is true, for example, for water-dependent climatic feedback mechanisms, such as cloudiness, ice and snow, and interactions of water vapor with radiative heating and temperature. These and other individual processes are active on other planets in different ways--and it is this difference that provides the opportunity to test physical or chemical theories developed for earth climate studies under a vastly different set of boundary conditions. If our theories are correct, they should be generalizable, and verification of their generality will provide additional confidence in those theories--a confidence that is urgently needed in earth climate studies.

In addition to the opportunity to test the generality of physical parameterizations derived from terrestrial experience, under vastly different conditions, planetary science has already provided a number of examples in which the experience and skills developed in the study of other planets has accelerated progress in the understanding of terrestrial problems. Speed in narrowing the uncertainties surrounding estimates of various earth climatic theories has become a clear need in view of such possible human influences on climate as the potential for alteration of the ozone layer or of changing the heat balance by increasing the CO₂ concentration. Research in both problem areas has already benefited from the existence of a planetary research program. For example, study of the radiative properties of CO₂ for the conditions on Venus led to a parameterization of the CO₂ influence on radiation. Although originally intended for Venus application, this parameterization has subsequently been widely used for calculations in the earth's stratosphere. Undoubtedly, such a development would eventually have occurred independently for earth, but the existence of a scientific effort in planetary atmospheres speeded up the process considerably. In fact, much of radiative transfer theory now in common usage in earth applications was originally developed for extraterrestrial applications.

Similarly, the very rapid progress in modeling the earth's ozone shield and the potential for its disturbance by human pollutants owes some of its development speed to the pre-existing efforts of researchers who were actively studying the chemistry of planetary atmospheres. This community of researchers, largely dedicated to "pure" basic research, was able to take advantage of the generality of their planetary theories, techniques, and knowledge. They were quickly mobilized to work on the earth's ozone problem in response to a pressing national need for such assessments. Again, the planetary researchers provided a basic resource that significantly speeded up the process of earth-oriented assessments.

As another specific example, one component of some earth climatic theories is the parameterization of horizontal and vertical heat fluxes as functions of the large-scale thermal forcing. Some of these theories which

are at the core of highly parameterized earth climate models, were originally developed in the context of comparative planetary studies. The point is not that such parameterizations are necessarily "correct," or even "optimal," but they have generated controversy and have stimulated others to explore this problem. In other words, the nature of these contributions has been similar to that of basic research in all fields. In this way, they have also speeded the development of earth-oriented theory. Since their original context was planetary atmospheres in general, they have drawn together researchers from terrestrial and other planetary perspectives, a broadening of the skills and viewpoints that seems likely to improve progress in both areas of study. In part, this Workshop and its report are illustrative of such combining of talents.

Although studies of planetary atmospheres in general are not per se sufficient for development of earth-oriented climate theories, the claim that planetary studies will have considerable "spin-off" for earth climate theory development already has been demonstrated. The feedback between studies of the earth's atmosphere and the atmospheres of other planets works both ways. What we learn from other planets may help to build understanding of the terrestrial climate. An improved understanding of the earth's atmosphere can help us to understand the other planets. This process has hardly begun. Only since the advent a decade or so ago of earth and extraterrestrial space vehicles and large data processing systems has the scientific community had the tools with which to mount a serious effort to develop a climate theory--for the earth or other planets. Although much of the knowledge gained from planetary observations has yet to be fully exploited for the understanding of individual planetary atmospheres, the more ambitious goal of developing a general theory of planetary climates through what may be called the science of comparative planetary climatology now lies open before us.

SECTION VI

SUMMARY

Interest in terrestrial climate and the factors influencing climatic change has grown rapidly in the public at large and within the scientific community. In part, this is a consequence of the recognition of the sensitivity of the global environment to human influences; in part, it follows from a growing awareness of the increase in sensitivity of the world economy to climate changes which result from population increases and the increasing complexity of the economy. During this same period much has been learned about the atmospheres of the planets, and this new knowledge can aid in the formulation of theories of season-to-season weather variations and longer-term climatic change. It is certainly not necessary to explore the planets in order to answer questions concerning terrestrial weather and climate. Presumably we would continue to seek answers to these questions even if there were no other planets. But the planetary knowledge helps in two ways:

- (1) Simulation models and mechanistic models can be applied to other planets as well as to the earth. If the actual circulations of the planetary atmospheres are known, this application provides a means of testing model performance under very different conditions. In so doing, this helps to validate use of the models to examine climate, when the external conditions governing climate are very different from those of the present.
- (2) Many physical processes which occur in the earth's atmosphere also occur in the atmospheres of other planets, but in a more extreme form. The study of planetary atmospheres helps us to gain a better fundamental understanding of such processes, and perhaps even to identify terrestrial processes which would otherwise be missed.

Of the three atmospheres which have been investigated by planetary probes, that of Mars is best understood. It exhibits global temperature variations and wind systems which are similar in many respects to the earth's. The distribution of temperature (as distinct from its average value) differs from that of the earth mainly as a consequence of the absence of Martian oceans. In addition there are internal gravity waves, thermally driven tides, synoptic-scale storm systems, and topographically forced planetary scale disturbances which can be related to comparable systems on earth. Mars is unique in having global-scale dust storms, which are indicative of a close coupling between radiative heating, removal of dust from the surface, and planetary-scale wind systems. Surficial evidence for different past climates may provide clues to the long-term evolution of terrestrial climate.

Venus' deep cloudy atmosphere has a circulation radically different from that of the earth or Mars. Its most striking large-scale feature is the rapid east-to-west rotation at the level of the cloud tops in spite of very slow rate of rotation of the solid planet. There is also abundant

evidence for both waves and convection in the cloud top structures. Recent attempts to model Venus' circulation have achieved some successes and suggest that the rotational velocity of the upper atmosphere is maintained by a complex system of interactions between planetary scale waves, small-scale turbulence, and the zonal flow itself. The physical, chemical, and dynamical processes responsible for maintaining the Venus cloud layers remain largely mysterious. Since the clouds control the distribution of radiative heating which, in turn, acts to drive the large-scale circulation, understanding of these processes is fundamental to understanding the circulation. Enough is known about the Venus clouds that a number of analogies with terrestrial aerosol and cloud processes have already been identified.

Jupiter has been least explored. The most prominent features are the zonal bands known as belts and zones. These exhibit disturbances and eddies at various scales, many of which appear to move with the wind at cloud-top level, and such motions have helped to delineate the large-scale flow pattern. At polar latitudes this pattern gives way to one of smaller-scale features which are not necessarily zonally aligned. Several Jovian features which are of particular dynamical interest are: the large scale of the planet which may allow a relatively broad spectrum of atmospheric motions to develop, the important connection between clouds and circulation in the control exerted by the clouds on the radiative heating distribution, and possibly in their latent heat release as well, the great depth of the atmosphere, and the influence of the internal heat source on circulation.

Observational goals were defined for each planet. For Mars, these are:

- (1) To verify or refute the predictions of current dynamical models.
- (2) To refine our knowledge and understanding of polar and dust storm processes.
- (3) To determine the paleoclimate of Mars.

For Venus, the observational goals which were identified are:

- (1) To determine, more completely, the vertical and horizontal distributions of radiative heating and cooling, and the relationship of radiation fluxes to clouds.
- (2) To define a mean atmospheric state, including the large-scale mean wind distribution.
- (3) To define the smaller-scale and transient wind systems and identify their mechanisms.
- (4) To discover whether clues to past atmospheric processes are imprinted in the surface.

The goals for Jupiter are:

- (1) To determine the rates and the vertical extent of heating and cooling and the relative importance of the solar and internal heat sources at different levels.
- (2) To determine the mean state of the atmosphere.
- (3) To determine the structures of the cloud and motion fields over a broad range of scales and at depths below the cloud tops.